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Tornadic waterspout at the Jebel Ali Sailing Club

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Summary

At approximately 2215 GMT on 15 March 1986, a tornadic waterspout tracked through the boat park of the Jebel Ali Sailing Club, situated 25 km south-west of the city of Dubai in the United Arab Emirates. This article describes the synoptic situation leading up to the development of the storm and its devastating effects, and aims to provide some useful indicators for local meteorologists to help them in the difficult task of forecasting these severe storms, and any associated tornadoes and tornadic waterspouts.

1. Introduction

The Emirate of Dubai (see Fig. 1) is situated just to the north of the Tropic of Cancer on the south-eastern shore of the Arabian Gulf (formally better known as the Persian Gulf), and is one of the seven emirates in a federation established in 1971 called the United Arab Emirates (UAE). Here the weather is dominated for much of the year by the subtropical high pressure belt, producing subsiding air, clear skies and generally weak pressure gradients which, in turn, produce regular land and sea breezes shunting large amounts of evaporated Gulf moisture back and forth across the flat coastal plains. Summers are very hot and humid with daily maximum temperatures frequently exceeding 45 °C, making life in summer without the assistance of air conditioners rather unpleasant, if not unbearable, for most Europeans. Blue skies persist throughout the summer with the moisture confined to the lower levels of the atmosphere beneath the subsiding drier air aloft. By contrast, winter weather in the UAE is very pleasant, comparing favourably with the best British summers. Rainfall is scanty and very variable from year to year with means of around 100 mm along the coast and somewhat higher values near the Hajar Mountains which run northwards along the east coast of the UAE up into the Omani Musandam Peninsula. Much of this rainfall is produced ahead of eastward moving shemal troughs or pseudo cold fronts driven by long-wave upper troughs which sweep these latitudes in winter with the annual southward migration of the subtropical jet stream.

Quite often these winter troughs produce little in the way of much needed rainfall or even cloud. However, in the case described here, there was not only a substantial amount of rainfall but also the relatively rare occurrence of a tornadic waterspout which fortunately led to no loss of life, though it did cause a considerable amount of damage to the Jebel Ali Sailing Club.

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2. Synoptic situation

Fig. 2 shows that at 0900 GMT (1300 local time) on 15 March 1986, a surface trough was lying from the Yemen Arab Republic through central Saudi Arabia to Kuwait. Ahead of this trough, pressure was falling steadily. Pressure falls during the previous 24 hours were 5.0 mb at Dubai and Abu Dhabi, 6.3 mb at Doha and 7.7 mb at Ras Tannūrah (24-hour tendencies are used because of the large diurnal pressure variations in the tropics). The air mass in the lower Gulf region was very dry ahead of this trough, e.g. temperature 30 °C and dew-point 3 °C at Dubai. However, at 0900 GMT on 15 March 1986, along the Omani coast, Salalah was reporting a moderate south-east wind with temperature 30 °C and dew-point 23 °C, and Masirah was reporting a temperature of 27 °C and a dew-point of 21 °C.

At 1200 GMT, around mid-afternoon local time, freshening south-easterly winds ahead of the trough were already causing deteriorating visibilities due to dust haze or rising sand (see Fig. 3). Although the air mass was still relatively dry at Dubai and Abu Dhabi, higher dew-points were evident in the lower Gulf region at Bu Hasa, Asab and Jebel Dhanna, and also in the state of Qatar at Umm Said and Doha. The pressure gradient was strong enough to prevent the formation of the usual afternoon sea-breeze, a rare event for Dubai. As a result the maximum temperature was 32.6 °C at Dubai and 34.5 °C at Minhad, which was 4 °C above the mean maximum temperature for March, and the highest recorded temperature up to this date for 1986. Apart from small amounts of altocumulus, surface observations and satellite images in the afternoon showed little cloud development ahead of the trough.

At 0001 GMT on 16 March 1986, which is shortly after the storm, thunderstorms and rain were still occurring at Dubai and Ras Al Khaimah. To the west of the shemal trough, fresh to strong shemal (Arabic for northerly) winds were advecting a cooler air mass into the southern Gulf region (see Fig. 4), the temperature at Kuwait of 14 °C being 13 °C lower than the temperature at Abu Dhabi.

3. Upper-air flow

Analysis of the upper-air flow in the Middle East is handicapped by communication problems and by a dearth of radiosonde reports from underdeveloped and sparsely populated areas in north Africa and the Arabian peninsula. In addition to this, the continuing war between Iraq and Iran has resulted in a complete black-out of all meteorological observations from both these countries since the beginning of the war in September 1980. However, in the UAE there is a radiosonde station at Abu Dhabi which is only 90 km from the location of the tornadic waterspout.

The Abu Dhabi tephigrams for 1200 GMT on 15 March and 0001 GMT on 16 March 1986 (see Fig. 5) show an increase in moisture with time at lower levels but the air mass had remained quite dry above 550 mb. However, both ascents show potential instability, with wet-bulb potential temperatures decreasing with height above about 900 mb.

Analysis of the upper-air charts at 0001 GMT on 15 March 1986 showed a marked trough at 850 and 700 mb lying from north-central Saudi Arabia to Sudan with the 850 mb winds well backed to 180° / 15 kn at Jeddah on the Red Sea coast of Saudi Arabia. The trough at 850 mb appeared much sharper than at 700 mb and higher levels, and favourable for the entrainment of moister low-level air from the Red Sea, Gulf of Aden and the Arabian Sea. At 500 mb the upper trough was less pronounced and orientated through the northern Red Sea and central Egypt. No upper trough was evident at 300 mb; there was a zonal flow over the Arabian peninsula with the sub-tropical jet core maximum of approximately 140 kn situated over northern Saudi Arabia.

Fig. 6(a) shows that by 0001 GMT on 16 March 1986, the 850 mb trough had advanced eastwards to be orientated through the southern Arabian Gulf to the People's Democratic Republic of Yemen just about 60 n miles west of the surface position of the shemal trough, while the 700 mb trough (see Fig. 6(b)) was lying approximately 550 n miles further to the west, through central Saudi Arabia and the

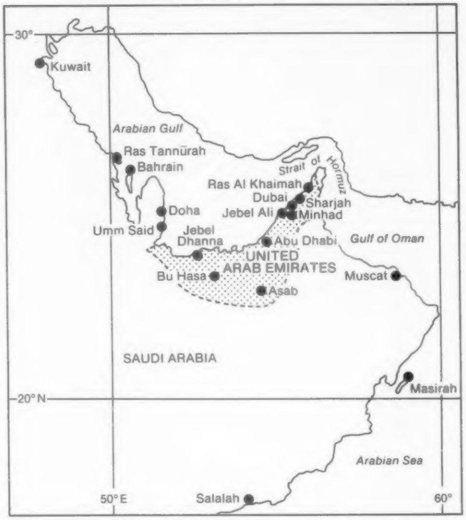

Figure 1. Map showing the relative positions of places mentioned in the text. The stippled area shows the extent of the United Arab Emirates.

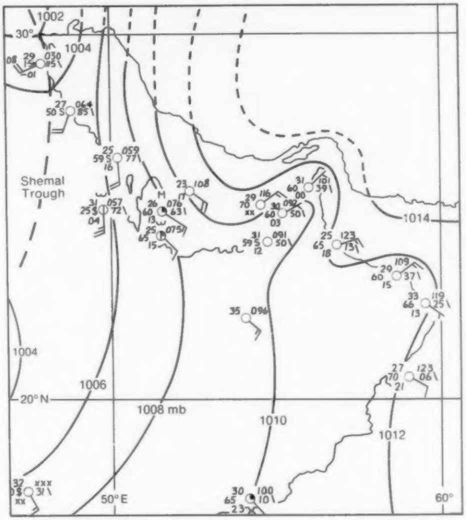

Figure 2. Surface analysis at 0900 GMT on 15 March 1986, with observations plotted (pressure tendencies are for the previous 24 hours).

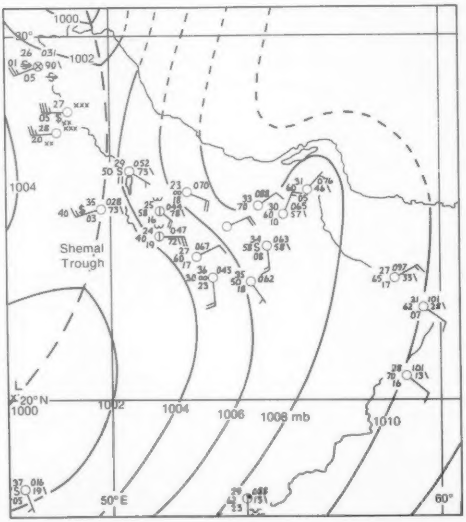

Figure 3. As Fig. 2 but for 1200 GMT on 15 March 1986.

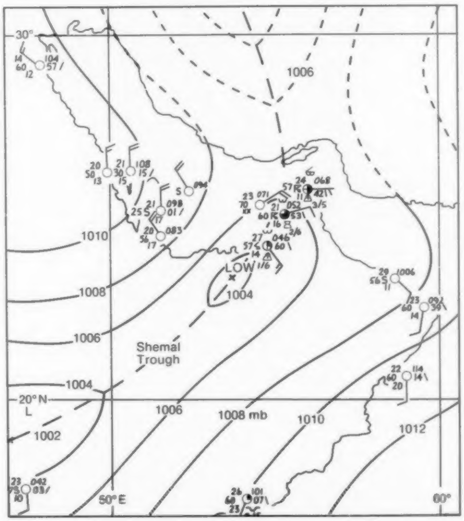

Figure 4. As Fig. 2 but for 0000 GMT on 16 March 1986.

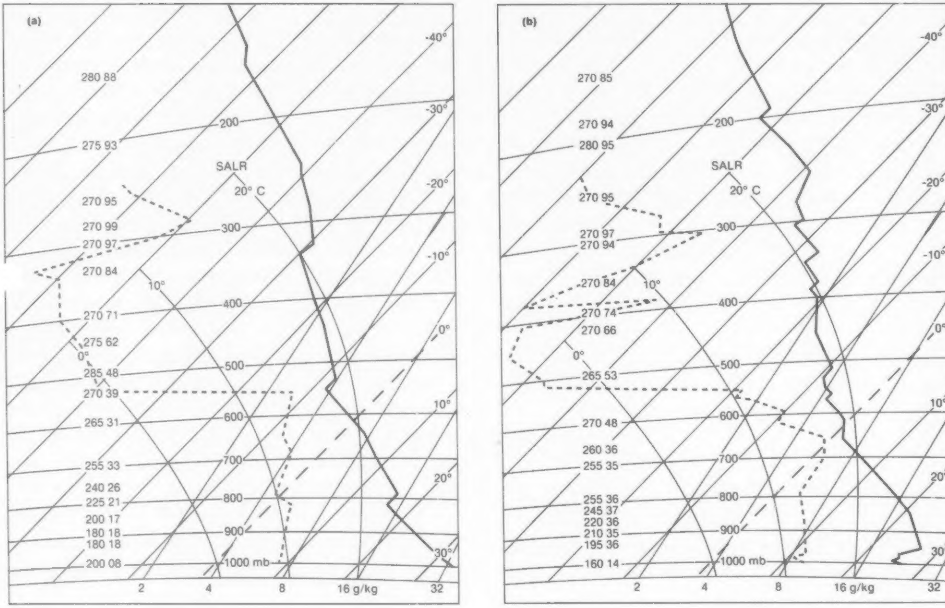

Figure 5. Radiosonde ascents for Abu Dhabi for (a) 1200 GMT on 15 March 1986 and (b) 0000 GMT on 16 March 1986.

Yemen Arab Republic. This indicates a steep leading edge to the cold air, not untypical of a fast-moving cold front of more temperate climes. A less-marked trough at 500 mb (see Fig. 6(c)) was lying through central Saudi Arabia, while at 300 mb a strong zonal flow was maintained (see Fig. 6(d)) with a westerly wind of around 100 kn over the Jebel Ali area.

4. The storm

At 2213 GMT on 15 March 1986, the first flash of lightning heralded the beginning of the storm over the Jebel Ali area. In the village on the periphery of the thunderstorm, lightning was observed mainly from altocumulus castellanus cloud but no precipitation was experienced, and the wind speed was estimated at less than 15 kn. However, at the 'one hundred beach villas', situated 5 km from the village and just to thc south of the Jebel Ali Sailing Club, thunder, lightning and heavy rain were observed. Winds in excess of 45 kn were measured on a roof-mounted anemometer before readings went off the instrument scale. At about the same time, hurricane-force winds were estimated to be 100–120 kn at the Sailing Club according to reports in the Khaleej Times on 17 March 1986. However, this may have been an overestimate. A better estimate is given by the damage caused; this suggests that the winds may have been in the range 63–97 kn, on the Fujita Scale F1 for Damaging Wind or TORRO force T2–T3 on the Elsom and Meaden Tornado Intensity Scale — a moderate to strong tornado. Heavy sailing dinghys and catamarans, which would normally take up to six people to lift, were picked up along with their launching trailers and scattered around the beach and boat park. In the harbour two cruisers were overturned and sunk, and a small cruiser parked on a road trailer was turned upside-down. Heavy

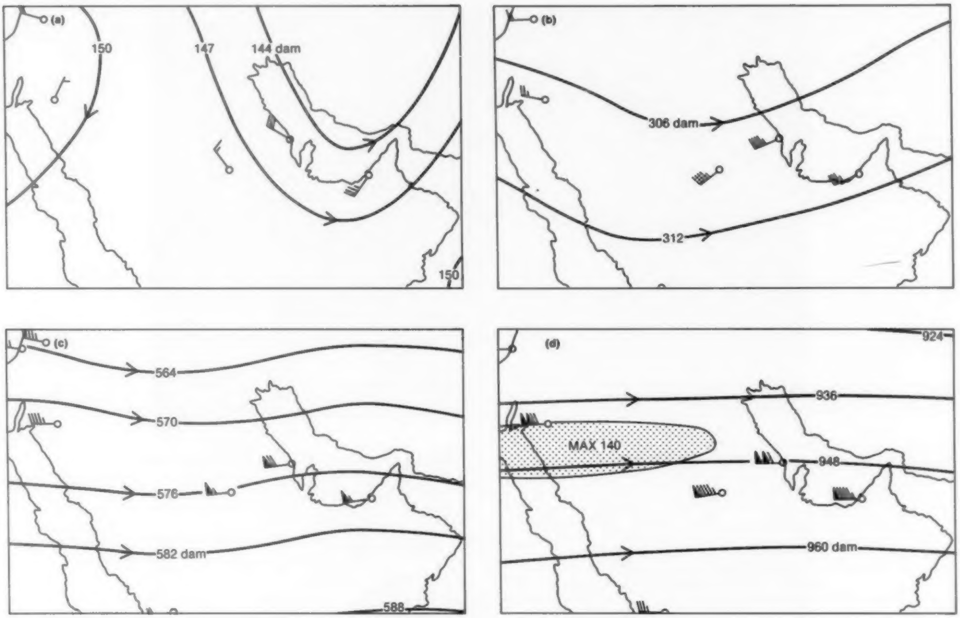

Figure 6. Upper-air analyses for 0000 GMT on 16 March 1986 for (a) 850 mb, (b) 700 mb, (c) 500 mb and (d) 300 mb (stippled region indicates speeds above 120 kn).

cable-drum tables, which were embedded in the sand in front of the club house, were hurled through the air and the gate-house was turned upside down and carried about 10 metres (see Fig. 7).

The final resting positions of the Wayfarer dinghy fleet and other debris after the storm gives some clue to the probable track of the tornadic waterspout funnel. These heavy sailing dinghys were all parked together at the top of the slipway before the storm. After the storm they were found in the positions shown in Fig. 8, to the east and north of the Wayfarer park. This implies that the tornadic waterspout funnel tracked in from the sea over the slipway in an east to east-north-east direction.

It is interesting to note that ahead of the upper trough, at 0001 GMT on 16 March 1986, the upper winds at Abu Dhabi were 220°/36 kn at 850 mb and 255°/35 kn at 700 mb.

NOAA-9 infra-red satellite images at 2327 GMT on 15 March 1986 (see Fig. 9) show numerous cumulonimbus cells over Dubai and the northern Emirates, and across the Gulf of Oman to southern Iran. Of particular interest is the Spembly density slice (Fig. 9(b)), which is a computerized video technique that enhances the NOAA-9 infra-red image shown in Fig. 9(a) and highlights the coldest cumulonimbus tops and the large multi-cell thunderstorms in the Jebel Ali area of the Dubai Emirate.

Around 0240 GMT on 16 March 1986, other cumulonimbus cells produced peanut-size hail in Bur Dubai, according to reports in a local newspaper, the Gulf News. At Dubai International Airport 15.8 mm of rainfall was measured overnight, while at Minhad only a trace of rainfall was recorded. By 0700 GMT the thunderstorms had cleared most of the northern Emirates and were followed by moderate to fresh north-westerly shemal winds and very hazy conditions. This sand and dust haze was

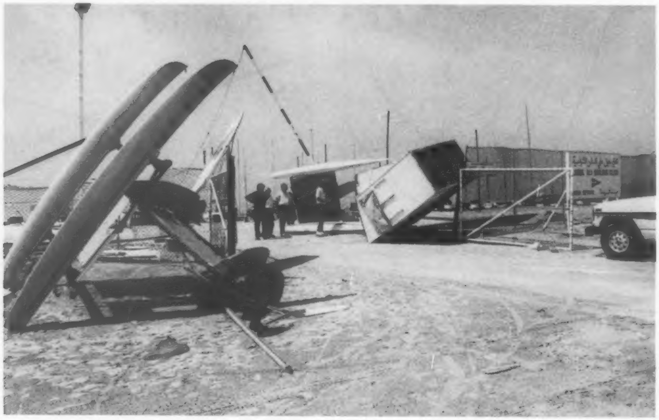

Figure 7. Photograph from the Khaleej Times showing the aftermath of the storm at Jebel Ali Sailing Club.

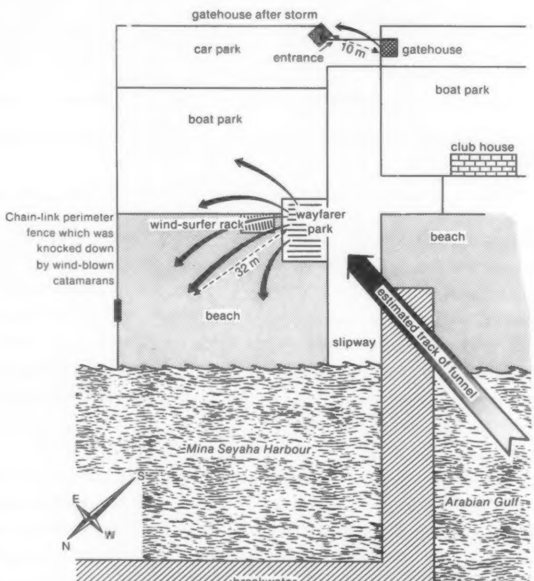

Figure 8. Plan of the Jebel Ali Sailing Club (not drawn to scale) showing movement of boats and gatehouse caused by the tornadic waterspout. Its estimated track is shown by the arrow.

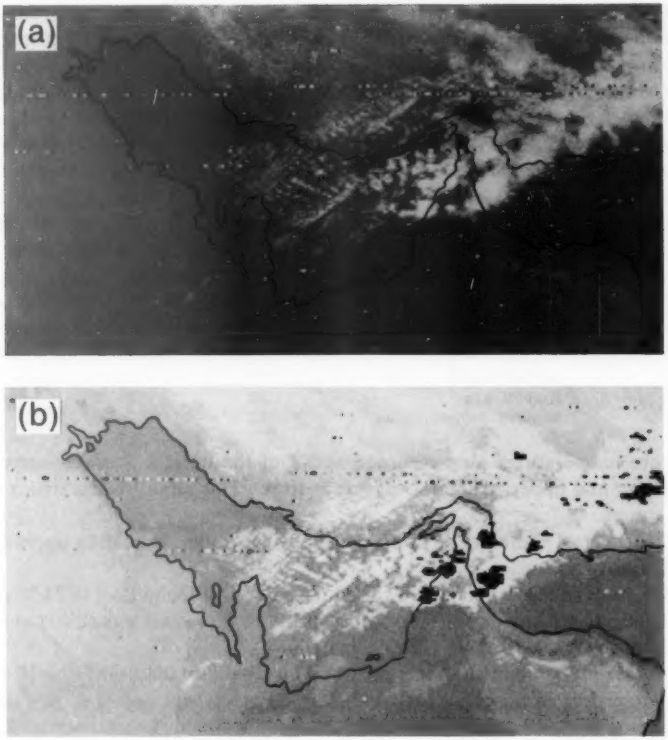

Figure 9. (a) NOAA-9 infra-red satellite image at 2327 GMT on 15 March 1986 and (b) Spembly density-slice image of the satellite picture.

raised by the strong winds 24 hours previously over the Lower Mesopotamian Plain and northern Saudi Arabia. It was then advected by the shemal winds 800–1000 km down the Arabian Gulf and reduced the visibility to 1000 metres or less in places in the UAE.

5. Discussion

The development of this tornadic waterspout was brought about by a combination of favourable circumstances. Some of the more important atmospheric conditions observed in this development were as follows:

(a) A mobile trough over the Arabian Peninsula at the surface, 850, 700 and 500 mb produced dynamical ascent ahead of the surface trough.

(b) The air mass was initially dry at the surface layers and moist at medium levels. Advection of moist surface air from the Arabian Sea and the Omani coast to the Asab, Bu Hasa, Jebel Dhanna area occurred only 6–9 hours before the storm development. This provided the necessary moisture to produce the cloud and precipitation often absent in the southern Arabian Gulf with approaching troughs.

(c) Winds were of jet-stream strength (60 kn or more) above 450 mb. The maximum wind in the vicinity of the storm was approximately 270° / 100 kn and occurred around 300 mb. At this level the jet stream removes air so quickly that air from below is drawn up to replace it thereby enhancing convection. However, from Fig. 6(d) it is not apparent that the Jebel Ali area is in a strongly diffluent region such as a left exit or right entrance with respect to the 300 mb jet.
(d) Vigorous warm advection was evident ahead of the trough. Wind speeds below 500 mb increased with time. At lower levels winds were southerly, while above 650 mb the winds were westerly. Vertical wind speed shear was about 3 kn per 1000 ft between 700 and 300 mb. Although these particular values do not appear to be excessive, increasing wind speed with height and vertical wind direction shear are necessary requirements for the updraught inside the storm to rotate cyclonically.
(e) The air mass was potentially unstable ahead of the trough. Instability indices devised for use in the United Kingdom are also useful indicators for instability in winter in the Middle East.

	Index	Threshold
Boyden instability index	99	94/95
Rackliff index	30	29/30
Modified Jefferson index	32	26/28

(f) High surface temperatures were recorded ahead of the trough. Surface temperature contrast between the lower and upper Arabian Gulf was 6–10 °C. This established a strong baroclinic zone ahead of the trough.
(g) Pressure falls were 4–7 mb per 24 hours ahead of the trough, indicating upper-level divergence and ascent of the surface air.
(h) Sea temperatures in the Arabian Gulf varied from 21 °C at Doha Port to 24 °C at Sharjah Port. This may have also contributed to the instability of the air mass as it was advected over the slightly warmer waters of the south Arabian Gulf.
(i) The 850 mb wet-bulb potential temperature at Abu Dhabi for 0001 GMT on 16 March 1986 was 18.5 °C. It is interesting to note that David (1976)* observed that one of a number of parameters associated with severe storms which produced tornadoes in North America was an 850 mb wet-bulb potential temperature of 18 °C.
(j) To say that orography played no part in the development of the storm would be a bold statement, given the shape and natural features of the lower Gulf basin. It is surrounded by the Zagros Mountains of Iran to the north, the Hajar Mountains to the east and the gradual upslope across the Rub Al Khali or Empty Quarter, leading to the Hadhramaut Mountains of the People's Democratic Republic of Yemen and the Tihamah Mountains of Saudi Arabia and the Yemen Arab Republic. Indeed the only low-level outlet for any airstream from the Arabian Gulf is through that politically sensitive bottle-neck, the Strait of Hormuz and this in itself can often produce orographic troughs in the south Gulf region. However, on this particular occasion it would be imprudent to attribute too much influence to the orography, given the flat low-lying terrain of the coastal plain in the Jebel Ali area.

6. Conclusion

This article has attempted to summarize the main features of the synoptic situation concerning the development of this particular tornadic waterspout. Given the limited data and observations available to the bench forecaster working in the Arabian Gulf region, we can speculate that the parent

* David, C.L.; A study of upper air parameters at the time of tornadoes, *Mon Weather Rev*, **104**, 1976, 546–551.

thunderstorm which spawned this waterspout was triggered by displacement of the warm air ahead of the trough. This air mass had been supplied with sufficient moisture by low-level advection from the Arabian Sea. The warm, moist air was then pushed aloft by the colder, denser air to the rear of the trough. Although it remains impossible to forecast the exact locations of these severe local storms and associated tornadoes and tornadic waterspouts, it is hoped that recognition of the features noted above will help Gulf forecasters to become more aware of the rapid and violent changes that can occur, given cloudless conditions over and to the west of this area only 6–9 hours before storm development.

Acknowledgements

Discussions with the following members of staff of International Aeradio plc during the preparation of this article are gratefully acknowledged: H. Rodda (Senior Met. Officer, Central Air Base Minhad), W.H. Owen (Senior Met. Officer, Dubai International Airport) and C.C.E. Jackson (Senior Met. Officer, Sharjah International Airport). Grateful thanks are also extended to the Commanding Officer, Central Air Base Minhad for permission to publish this article and to the Khaleej Times for the photograph showing the aftermath of the storm.

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Dynamics of the monthly-mean climate*

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Summary

The lay person might quite reasonably ask, 'Why are the winds in temperate latitudes predominantly westerly?' or 'Why do the major arid regions occur near 30 ° N (and S)?' When faced with such questioning how should the climatologist respond, or is causal explanation hopeless? In this article, the dominant physical processes and constraints are identified and, with some judicious simplification, a 'back-of-the-envelope' theory of the zonally-averaged general circulation is sought. It is argued that poleward momentum transport by large-scale weather systems plays a crucial role in driving the observed surface wind pattern and organizing the release of latent heat energy.

1. Introduction

One month is considered to be the smallest averaging time-interval that can be used for a local (in space) definition of climate to make sense. Implicit in this choice is the need to average over many baroclinic wave life cycles (life cycle time-scale ≈ 7 days). Ideally, one would like to explain all of the major time-averaged synoptic features, such as the Icelandic low and Siberian anticyclone in winter and the Azores anticyclone and Indian monsoon in summer, together with the positions of the major storm tracks. A physical understanding of the principal dynamical factors involved in determining the strength and position of these phenomena might then allow their inter-annual variability to be forecast. Whilst this is a rather ambitious goal, the idealized theoretical models developed along the way provide a dynamical framework with respect to which diagnostics can be developed and interpreted, e.g. Q-vectors (Hoskins *et al.* 1978). The classical approach has been to try to understand features of the zonally-averaged climate (e.g. three-cell mean meridional circulation) and relate them to heat and

* Lecture note from a series of lectures entitled 'Dynamical Processes in Meteorology' given as part of the 1986 Advanced Lectures (Meteorological Office, 15 September–3 October 1986).

momentum budget requirements. Since the zonally-averaged climatic fields represent much of the observed variation across the globe, it is important to have a dynamically-consistent picture of the underlying mechanics which determine them.

A few salient features of the global heat energy budget are examined in section 2 and various hypotheses concerning the magnitude of poleward heat transport and the observed meridional temperature gradient are reviewed. The role of poleward momentum transport is emphasized in section 3 and related to the zonal-mean distribution of surface pressure, wind and precipitation: a summary of how these eddy transfer processes determine the zonally-averaged state of the troposphere is then given in section 4.

2. Heat transfer

The latitudinal imbalance of net heating in vertical columns (extending into the ground/sea and throughout the atmosphere) is determined primarily by the geometrically-controlled variation of insolation and the weak latitudinal dependence of outgoing infra-red radiation. The latter is at least partly due to the dominance of water vapour amongst the other infra-red radiating tri-atomic molecules and the fact that the uppermost optically black layer of water vapour occurs at a temperature fixed by freezing and precipitation (≈ -18 °C). Much of the heat energy surplus in the tropics is not immediately available since solar radiation over large regions is absorbed into the upper few metres of the oceans. It is subsequently released to the atmosphere mainly through evaporation into the trade winds and ultimately converted to sensible heat and gravitational potential energy through condensation on ascent in deep tropical convection. The warming influence of this latent heat release is transmitted to tropical regions distant from the convection by forced subsidence in association with the radiation of inertia-gravity waves — particularly Kelvin and Rossby-gravity modes (Gill 1982).

Heat energy is removed from the subtropics in the familiar organized baroclinic weather systems of synoptic charts and quasi-stationary planetary wave systems (Shutts 1987). This type of large-scale 'sloping' convection (Green 1979) transfers heat polewards and upwards so as to balance the radiative sink in higher latitudes. During autumn and winter, the middle latitude oceans give up much heat energy stored in them during the summer, providing depressions with considerable latent heat energy which can be organized and released in 'explosive cyclogenesis'.

A simple zonally-averaged climate model much loved by the climatologist requires the tropospheric, depth-averaged temperature to be determined, given fixed or parametrized heat sources and sinks. From this temperature distribution, the thermal wind equation can be invoked to find a consistent wind field provided that some assumption is made about the surface wind, e.g. no flow. In these models, poleward heat transport is usually represented by a non-linear diffusion law where the eddy diffusion or transfer coefficient (Green 1970) is a function of the poleward temperature gradient. In fact, Green gives theoretical and observational support for the existence of a heat transfer law of the form:

$$\overline{v\phi} = 5.5 \times 10^{-3} \left(\frac{g}{B}\right)^{1/2} \Delta\phi^2 \text{ m s}^{-1}$$

where the overbar refers to a zonal, height, and time average, v is the meridional wind speed, g is the acceleration due to gravity, B is the mean static stability, ϕ is the logarithm of potential temperature and $\Delta\phi$ is the pole-equator difference in ϕ. In spite of being cast in the form of a diffusion law, Green's transfer theory is independent of mixing ideas.

Stone (1978) takes a very different viewpoint and suggests that baroclinic instability is super-efficient at transporting heat for temperature gradients in excess of a certain critical gradient, defined in

accordance with two-level quasi-geostrophic theory on a beta-plane. He argues that the observed poleward temperature gradients will never be far from this critical value since smaller gradients lead to very weak baroclinic instability which is unable to satisfy the global heat budget requirement and a slightly larger temperature gradient causes too much heat to be transported. This critical temperature gradient turns out to be proportional to the cotangent of latitude and to the static stability. Observational evidence is given in Stone's paper to support this 'baroclinic adjustment' hypothesis in middle latitudes.

Another interesting hypothesis concerning the zonal-mean temperature is that of maximum available potential energy generation (Lorenz 1960, Paltridge 1978 and Shutts 1981). Given heat sources and sinks which are themselves some function of temperature, it is hypothesized that the time- and zonal-mean temperature is such that the Available Potential Energy (APE) generation rate is a maximum. If, for instance, the time-mean diabatic heating rate $Q(y)$ can be written as:

$$Q(y) = -\gamma(\delta T(y) - \delta T_*(y))$$

where y is latitude, γ^{-1} is a time constant, δT is the temperature perturbation about some mean and δT_* is some known equilibrium temperature perturbation such that the mean of Q is zero, then the APE generation rate is proportional to:

$$\int Q\delta T\,\mathrm{d}y = -\gamma\int(\delta T - \delta T_*)\delta T\,\mathrm{d}y$$

which is a maximum if $\delta T = \frac{1}{2}\,\delta T_*(y)$. Of course in practice Q is not merely a function of δT and the detailed physics, e.g. cloud albedo, cannot be ignored.

3. Momentum transfer

A theory which predicts the latitudinal distribution of temperature is of very limited use since it fails to tell us anything about the sense of the winds at the surface and, by inference, the frictionally-induced mean meridional circulation. What is required is a dynamical model which can account for the time-mean surface westerlies of middle latitudes and easterlies in the subtropics. Since there are no internal atmospheric sources or sinks of momentum in the zonally-averaged sense, frictional stress and wave drag at the surface can only be balanced by the height-integrated flux convergence of momentum. Of course, the surface wind pattern exists because of the momentum transport, though observations alone do not show this. The poleward momentum transport required to maintain the mid-latitude surface westerlies is brought about almost entirely by large-scale eddies (quasi-stationary forced planetary waves and baroclinic instabilities) and only in the tropics is the mean meridional circulation important. Even then the very existence of the observed 'Hadley circulation' relies on the presence of large-scale eddy momentum transport and it is incorrect to think of it as an independent agency for transporting heat and momentum. The often quoted notion of the Hadley circulation as the 'flywheel of the general circulation' is misleading. It is simply an ageostrophic response resulting from the destruction of the zonally-averaged thermal wind balance by:

(a) diabatic heating in equatorial cumulonimbus,
(b) frictional deceleration of the trade winds,
(c) a net upper tropospheric sink of westerly momentum due to the poleward transport by large-scale eddies — this causes the trade winds and therefore (b), and
(d) radiational cooling in non-precipitating regions throughout the tropics.

The principal reason that eddy transport of momentum dominates the total height-integrated poleward momentum transport is that the net Coriolis torque

$$\int_{D} \rho f v \, dx \, dz$$

vanishes at any latitude since there must be no long-term mass flux polewards. (D refers to the region of the longitude–height plane above the surface.) The term

$$\int_{D} \rho v \frac{\partial \bar{U}}{\partial y} dz$$

which represents the poleward flux of relative momentum due to the mean meridional circulation is small except in the tropics (where ρ is the density and U is the zonal wind — the overbar denotes the zonal average). Fig. 1 shows latitude–height cross-sections of the poleward momentum transport split into (a) transient and (b) stationary wave contributions for January 1979 based on FGGE (First GARP Global Experiment) data. Note that the transient eddies transport momentum polewards (except north of 60° N) whereas the stationary waves have a pronounced equatorward component near 60° N. In general, eddy momentum transfer is vertically coherent with a strong peak near the tropopause. The height-integrated momentum flux convergence from these pictures implies a westerly momentum sink at the surface between 30° and 60° N (in the time-mean) and an easterly sink between the Equator and 30° N. The pattern of zonal winds observed in that month (Fig. 2) was consistent with this required surface momentum exchange — representing as they do the normal climatological picture.

The zonally-averaged pressure field consistent with this distribution of zonal winds (through geostrophy) implies a low pressure belt at 60° N and a subtropical anticyclone belt at 30° N. Frictionally-induced ageostrophic motion at the surface then suggests that the former regions will be cloudy and wet and the latter clear and dry.

The transport of momentum by large-scale eddies is therefore crucial to the determination of the mean state of the atmosphere. The question that dynamical meteorologists have tried to address for at least 40 years is, 'What dynamical principles govern the sense of the momentum transport?' Many different ways of interpreting the tendency of baroclinic waves to transport momentum polewards have been proposed — all of which seem perfectly plausible. Most depend upon the existence of a 'beta-effect', i.e. variation of the Coriolis parameter with latitude. It can be shown that disturbances forced in mid-latitudes will tend to propagate as Rossby waves towards the Equator and in the process exhibit a marked north-east to south-west orientation — the signature of poleward momentum transfer (Hoskins *et al.* 1977). Baroclinic instability can, to some extent, be regarded as an initial disturbance energy-growth phase associated with the conversion of zonal to eddy-available potential energy followed in the mature phase by upward and equatorward Rossby wave radiation (Edmon *et al.* 1980).

The polar easterlies north of 60° N are not a very important aspect of the general circulation since they only occupy a small area of the earth's surface and are highly variable from month to month. Even so, they appear to be consistent with the observed equatorward flux of momentum in high latitudes, particularly by the stationary waves.

4. Summary

The zonally-averaged mean state of the troposphere can be thought of as being governed by two eddy transport properties:

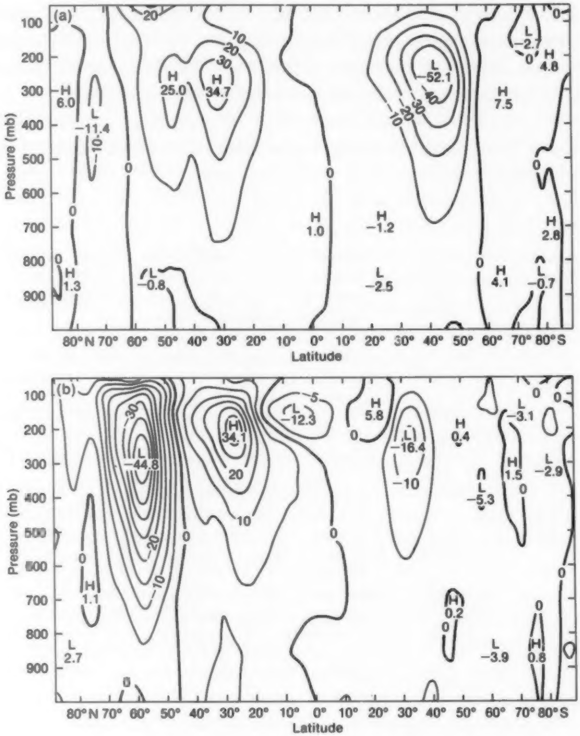

Figure 1. Latitude–height cross-section (zonally-averaged) of (a) transient and (b) stationary eddy momentum flux (m s^{-1})^2 for January 1979, based on FGGE data and derived through the ECMWF analysis system.

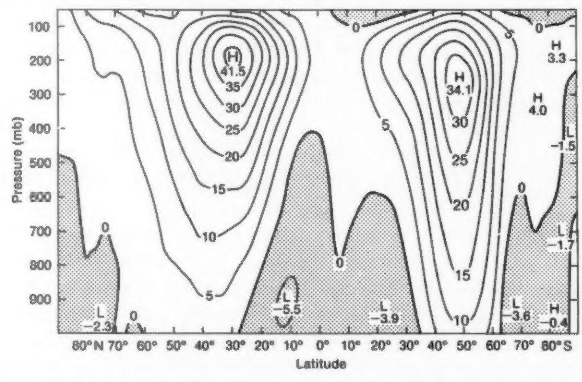

Figure 2. The zonally-averaged zonal component (m s^{-1}) of the wind vector corresponding to Fig. 1. Stippling indicates zonal-mean easterlies.

(a) The height-integrated poleward momentum flux which determines the surface winds.
(b) The height-integrated poleward heat flux which gives, through the thermal wind relation, the mean vertical wind shear — though parametrized relations between the surface stress and wind, and the temperature and heat source are required to complete the description.

Longitudinal variations of eddy heat and momentum transport are currently thought to contribute strongly to the zonal asymmetry of the mean circulation in addition to the topographical forcing functions discussed by Shutts (1987).

References

Edmon, H.J., jun, Hoskins, B.J. and McIntyre, M.E.	1980	Eliassen-Palm cross-sections for the troposphere. *J Atmos Sci*, **37**, 2600–2616.
Gill, A.E.	1982	Atmosphere–Ocean Dynamics. International Geophysics Series, Vol. 30, London. Academic Press.
Green, J.S.A.	1970	Transfer properties of the large-scale eddies and the general circulation of the atmosphere. *Q J R Meteorol Soc*, **96**, 157–185.
	1979	Topics in dynamical meteorology: 8. Trough-ridge systems as slantwise convection (1). *Weather*, **34**, 2–10.
Hoskins, B.J., Draghici, I. and Davies, H.C.	1978	A new look at the ω-equation. *Q J R Meteorol Soc*, **104**, 31–38.
Hoskins, B.J., Simmons, A.J. and Andrews, D.G.	1977	Energy dispersion in a barotropic atmosphere. *Q J R Meteorol Soc*, **103**, 553–567.
Lorenz, E.N.	1960	Generation of available potential energy and the intensity of the general circulation. *In* Pfeffer, R.L. (ed.); Dynamics of Climate, Oxford, London, New York, Paris, Pergamon Press.
Paltridge, G.W.	1978	The steady-state format of global climate. *Q J R Meteorol Soc*, **104**, 927–945.
Shutts, G.J.	1981	Maximum entropy production states in quasi-geostrophic dynamical models. *Q J R Meteorol Soc*, **107**, 503–520.
	1987	Linear models of stationary planetary waves forced by orography and thermal contrast. *Meteorol Mag*, **116**, 61–74.
Stone, P.H.	1978	Baroclinic adjustment. *J Atmos Sci*, **35**, 561–571.

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Random walk models of atmospheric dispersion

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Summary

Random walk models are being increasingly exploited as a means of simulating the dispersion of material in the atmosphere. In this paper a description of the random walk approach is given and its advantages and limitations discussed. To illustrate the approach, three examples of applications of random walk models are presented.

1. Background

There is a wide range of man's activities which either involve the release of substances into the atmosphere or have the potential for such releases; an understanding of atmospheric dispersion is important both in planning such activities and in responding to accidental discharges. The range of dispersion problems is large. For example, one might be interested in dispersion over a few hundred metres in the event of a tanker accident or over several thousand kilometres in the case of acid rain. To understand these different problems requires an understanding of the atmospheric eddies over a wide

range of scales, from the turbulence of micrometeorology to synoptic-scale depressions and anticyclones. Further complications are the chemical properties of the dispersing substances (which affect, for example, the rate at which the substance is absorbed by the ground) and the density of the release (as typified by the difference between hot buoyant plumes from chimneys and releases of dense gases such as chlorine).

So-called 'random walk' models constitute a promising approach to some of these problems; however, the range of problems to which such models are applicable is rather modest compared with the full range of dispersion problems. These models assume that the dispersing material is passive (i.e. it moves with, and does not affect, the flow) and that the eddies have at least some of the properties of randomness characteristic of three-dimensional turbulence. Thus they are not directly applicable to buoyant or heavy plumes, or to long-range problems where the eddies responsible for the dispersion are predominantly two dimensional. The main area of application of random walk models is to the dispersion of a passive substance in the turbulent boundary layer of the atmosphere.

Before discussing random walk models, it is appropriate to review the alternative methods which have been applied to the dispersion problem. Perhaps the most widely used method from a practical viewpoint is the Gaussian plume model, in which the shape of the concentration distribution across the plume is assumed to be Gaussian, i.e. a normal distribution. The width of the plume in the lateral and vertical directions is determined from tables or nomograms based on experimental observations of plume behaviour. Although it will be a while before this method is superseded from a practical point of view, such models are essentially empirical and do not explain the dispersion in terms of the flow properties. A second approach which has been extensively applied is the use of the diffusion equation. In this approach, it is assumed that the turbulent flux of material is proportional to the concentration gradient, the constant of proportionality being the diffusivity K. There are various ways in which K and its spatial and temporal variation can be estimated in terms of the flow properties. However, the fundamental assumption underlying the diffusion equation, namely that the length- and time-scales of the motions responsible for the dispersion are small compared with the scales on which the concentration and flow properties vary, is not true in general. This leads to a number of qualitative errors in the results. For example, a plume from an elevated source grows linearly for small times after release (because fluid elements travel in straight lines over short distances) whereas the diffusion equation predicts parabolic growth as in Fig. 1. Also, in a convective boundary layer, a large part of the turbulent energy is contained in eddies whose sizes are comparable to the boundary-layer depth; as a result the diffusion equation fails to represent the most important qualitative features of the dispersion (see section 3). High-order closure models constitute a promising technique which overcomes some of the problems associated with eddy-diffusivity models. However, these models cannot represent the initial stages of the dispersion in a natural way and cannot easily represent the dispersion from complex source distributions (Deardorff 1978). There are a number of other techniques available such as similarity theory and Taylor's statistical theory, but these are of limited applicability. All these methods are discussed in more detail by Pasquill and Smith (1983). Random walk techniques provide a method of overcoming the most serious problems in the other approaches.

One does not have to watch a turbulent flow for long to realize that there is little hope of being able to predict the evolution of the flow in detail over a period of time much in excess of the time-scale of a single eddy. The usual response to this problem (which is adopted in random walk models and which is also implicit in the Gaussian plume and diffusion equation models) is to abandon any attempt to calculate the evolution of a particular flow and to concentrate instead on statistical quantities. More specifically the flow is considered to be one realization of an ensemble of flows in which the external conditions (e.g. geostrophic wind, lapse rate and surface conditions) are identical but in which the details of the turbulence differ. Attempts are then made to predict ensemble-average quantities such as the ensemble-

mean concentration of the dispersing material at a particular point P (this will be denoted by C(P)) or the standard deviation of the concentration at P (denoted by σ_c(P)). It is important to realize that C(P) is not necessarily equal to the concentration in any particular realization (Fig. 2); this is why an estimate of the variability in the concentration between the realizations, such as σ_c(P), is of some importance. In spite of this, most of the effort which has been devoted to understanding dispersion, including the study of

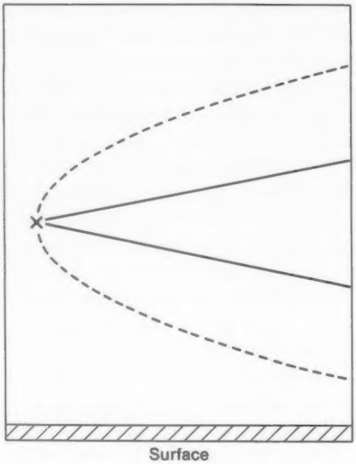

Figure 1. Plume growth downwind of an elevated source in the atmospheric boundary layer. The solid line indicates the true behaviour and the dashed line the result of using the diffusion equation. X marks the source position.

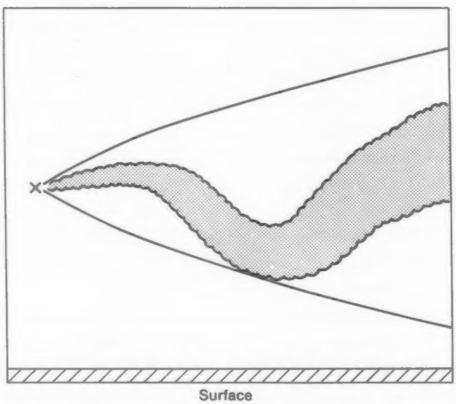

Figure 2. An illustration of the relation between the instantaneous plume in a particular realization and the ensemble-average plume. The shaded area indicates the instantaneous plume and the solid line denotes the boundary of the ensemble-average plume. X marks the source position. The ensemble-average plume width is generally larger than the instantaneous width because of the tendency of the plume to meander.

random walk models, has been directed towards predicting C(P), and this emphasis on C(P) is reflected in the current article. The more difficult problem of estimating σ_c(P) using random walk methods is discussed briefly in section 4.

2. What is a 'random walk' model?

The basic idea behind random walk models is to simulate the motion of many particles of the dispersing substance. Fig. 3 shows some simulated trajectories for the case of an elevated source in a neutral boundary layer. The particles are assumed to be drawn at random from among all the particles of the dispersing material in the ensemble of flows; hence they move independently. To calculate the ensemble mean concentration at point P, a small box is constructed (metaphorically speaking) around the point and the number of trajectories passing through the box is counted. In order to obtain statistically reliable values for the concentration it is necessary to ensure that many particles pass through the box. This means that it is impossible to make the box infinitesimal and hence the resulting concentrations are not point values but always averaged over some region. In order to be able to make these regions small, a large number of trajectories, typically ten thousand, are calculated.

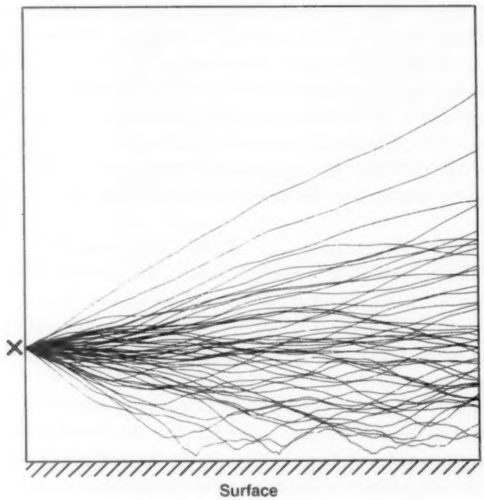

Figure 3. 50 trajectories from a random walk simulation of dispersion downwind of an elevated source, marked X, in a neutral boundary layer.

To implement the above scheme it is necessary to have a model of the way the particles move. One of the simplest schemes is that suggested by Langevin (1908) in connection with the study, not of turbulent dispersion, but of Brownian motion. In finite difference form, Langevin's equation for the vertical velocity of a particle (for simplicity only the vertical velocity is considered here) takes the form

$$w(t+\Delta t) = (1 - \Delta t/\tau)w(t) + r \quad \dots \dots \dots \dots \dots \dots \quad (1)$$

where $w(t)$ is the vertical velocity of the particle at time t, Δt is the time step, τ is a time-scale

characteristic of the particle motions and r is a normally distributed random number with mean zero and prescribed variance. The height of the particle at time t can then be calculated from

$$z(t+\Delta t) = z(t) + w(t)\Delta t.$$

The physical interpretation of equation (1) is that over a period Δt the particle loses a small fraction $\Delta t / \tau$ of its momentum to the surrounding air and in return receives a random impulse r. By choosing the variance of r appropriately, it is possible to ensure that the variance of the vertical velocity of the particles has the correct value. Of course a random walk model cannot predict properties of the mean flow and turbulence (such as the velocity variance or the time-scale τ); however, given this information, the random walk model can predict the dispersion.

Although this is not an appropriate place to discuss in detail the formulation of more general models, it is worth pointing out that the simple model given by equation (1) is not adequate in many situations. Consider, for example, a horizontally homogeneous situation where there is a gradient in the vertical velocity variance. Under these conditions the particles passing through a given point have, in reality, a non-zero mean vertical acceleration even though the mean vertical velocity at every fixed point is zero. To obtain realistic results it is necessary to include this non-zero mean acceleration in the model; failure to do so results in a model where a tracer which is initially well-mixed becomes 'un-mixed' and non-uniform in space at later times. The way in which a random walk model should be designed to take account of this and other similar effects is now well understood (Thomson 1984, van Dop *et al.* 1985, Thomson 1987). In essence, the model must be designed so that it does not lead to paradoxes if it is assumed that all 'particles' of air, and not just particles of the dispersing material, move according to the model. Models which are designed in this way agree with many of the exact results known in dispersion theory; this gives us some confidence that the models are capturing the essential physics of the dispersion process.

Random walk models have a long history. The idea that it is possible to explain the evolution of the concentration field by studying the statistics of the motions of fluid elements is due to Taylor (1921), who also discussed what is essentially the simple model described above. The idea is a natural one, since it is, of course, the motion of the individual elements of the dispersing substance which determines the dispersion. However, it is only comparatively recently that the computational resources have become available to allow widespread application of the technique.

Random walk models are very simple in concept, but might perhaps be thought to be a little simplistic. However, as indicated above, random walk models are an improvement in some respects over sophisticated high-order closure models, as well as over the simpler Gaussian plume and diffusion equation approaches. This is because, in the terminology of high-order closure models, the advection terms (which are always approximated in high-order closure models) are represented exactly. A consequence of this is that random walk models can represent the near-source behaviour of a plume easily and realistically. It may seem a little inelegant to calculate the motion of several thousand particles explicitly, but it is not clear how this can be circumvented without losing some of the good properties of random walk models. In some simple situations, e.g. homogeneous stationary turbulence, C(P) can be calculated analytically from the model equations but this is not so in most cases of practical interest.

3. Applications

Random walk models have now been tested in a wide range of situations. Three examples are described below, two involving dispersion over flat ground (in the surface layer and throughout the depth of a convective boundary layer) and one example over more complex terrain.

3.1 *Vertical dispersion in the surface layer*

In the surface layer of the atmosphere, which occupies typically the lowest few tens of metres of the atmosphere, the properties of the flow are well understood and are determined by three quantities: the roughness length, the surface heat flux and the surface stress. This knowledge of the flow can be used to construct a random walk model along the lines indicated in section 2 (Ley and Thomson 1983). Fig. 4 shows comparisons between the modelled vertical dispersion and that observed during the Project Prairie Grass experiment (Barad 1958) at 100 m downwind of the source. The three graphs show the dispersion under different stability conditions, with the Monin–Obukhov length, a standard measure of stability which is infinite in neutral conditions, taking values of 8 m (very stable), −87 m (slightly unstable) and −7.7 m (very unstable). Although there are some small differences, the model results show encouraging agreement and vary correctly with stability (note the different vertical scales — the variation of the dispersion with stability is quite substantial).

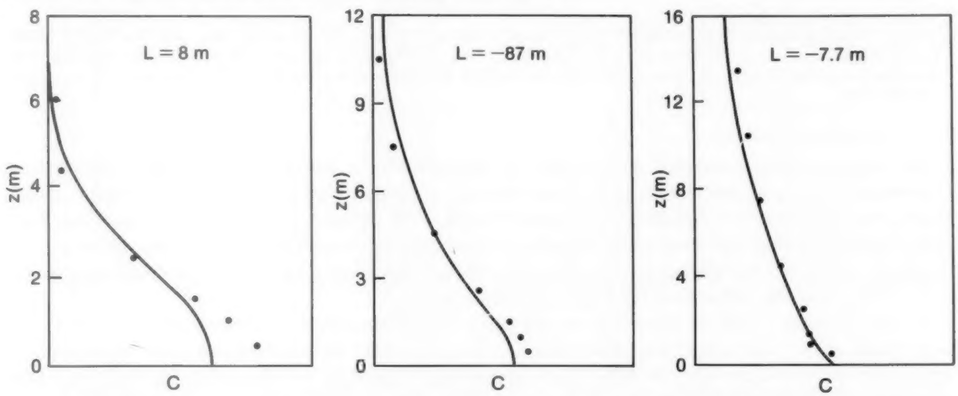

Figure 4. Comparison between the modelled vertical dispersion and that observed during the Project Prairie Grass experiment (taken from Ley and Thomson 1983). The concentration C is in arbitrary units, L is the Monin–Obukhov length and z is the height above the ground. The solid line indicates the model's behaviour and the dots the observations.

3.2 *Vertical dispersion in a convective boundary layer*

In a convective boundary layer the turbulence structure is dominated by large eddies comparable in size to the boundary-layer depth. These take the form of narrow vigorous updraughts surrounded by regions of slowly descending air. This flow structure results in a strong increase in the vertical velocity variance with height in the lower part of the boundary layer and a positive skewness in the vertical velocity distribution at all heights. The dispersion in such circumstances is quite complex.

Recently de Baas *et al.* (1986) have applied a model of the type outlined in section 2 to this problem. The results are shown in Fig. 5 for sources at two different heights. The results agree well with the experimental data of Willis and Deardorff (1976, 1981). Two features of the dispersion deserve comment. When the source is near the ground the plume centre-line lifts off the ground while, for an elevated source, the height of the maximum concentration descends to near ground level. This means that at a downwind distance of $z_i U/w_*$ (where z_i is the inversion height, U the mean boundary layer wind and w_* the convective velocity scale which is typically 1 m s^{-1} in a moderately convective boundary layer) the ground-level concentration is greater for an elevated source than for a source at ground level. These features are good examples of aspects of dispersion which are not represented at all in simpler models such as Gaussian plume and diffusion equation models.

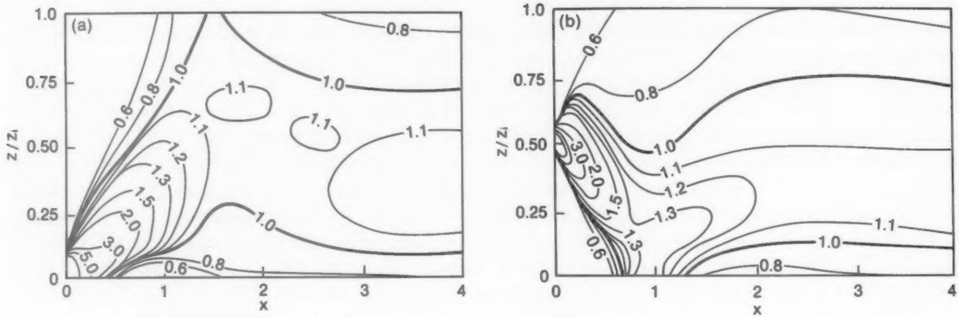

Figure 5. Model contours of concentration downwind of a source in a convective boundary layer for two source heights (a) $z/z_i = 0.067$ and (b) $z/z_i = 0.49$ (taken from de Baas *et al.* 1986). z is the height above ground and x is the downwind distance, non-dimensionalized by z_iU/w_* where z_i is the inversion height, U is the mean boundary-layer wind and w_* is the convective velocity scale.

3.3 *Dispersion in a valley*

The third example presented here is that of dispersion in a valley. Between 1980 and 1983 an experimental study of the flow properties and dispersion characteristics in the Sirhowy Valley , South Wales, was undertaken by the Boundary Layer Branch of the Meteorological Office (Mason and King 1984, Callander 1986). The flow in the valley is complex. When the wind blows across the valley the flow separates, with a recirculating eddy occurring in the lee of the high ground. Also the turbulence intensity in the valley is much larger than is found over flat terrain.

A random walk model of dispersion in the valley was constructed (Thomson 1986a) utilizing the knowledge of the flow which had been obtained from the field experiment and from the modelling studies of Mason and King (1984). Fig. 6 shows the variation of concentration with distance downstream, as obtained from the model and from the experimental data. Also shown are the concentration levels which would be expected over flat ground, as taken from Turner's (1969) Gaussian plume model. Two situations are considered, namely the release of material from the summit upwind of the valley (Fig. 6(a)) and from the valley floor (Fig. 6(b)), with the wind blowing across the valley and the static stability close to neutral. For the summit release, the model shows a substantial reduction in concentration compared to what would be expected over flat ground. Although the scatter in the experimental data is too great to make a detailed quantitative comparison, the data shows the same trend. For the valley release, the model predicts concentrations which are larger than those observed by a factor of about three. However, this error is small compared with that which would be obtained by using a Gaussian plume model designed for flat terrain. Such a model would overestimate the concentration by a factor of 25 if the summit wind speed was chosen as the appropriate wind speed for use in the model, and by a factor of 80 if the wind speed at the source was used.

4. Fluctuations in concentration

Fluctuations in concentration are often comparable with, or larger than, the mean concentration. This can be of great importance in situations where the dispersing substance is explosive or toxic. Consider, for example, a steady source of an explosive gas. The risk of an explosion will be related more to the peak values of the concentration than to the ensemble- or time-average value. Random walk models can predict a measure of the size of the fluctuations, namely σ_c, if the motions of pairs of particles, instead of single particles, are simulated. The idea that σ_c can be expressed in terms of the

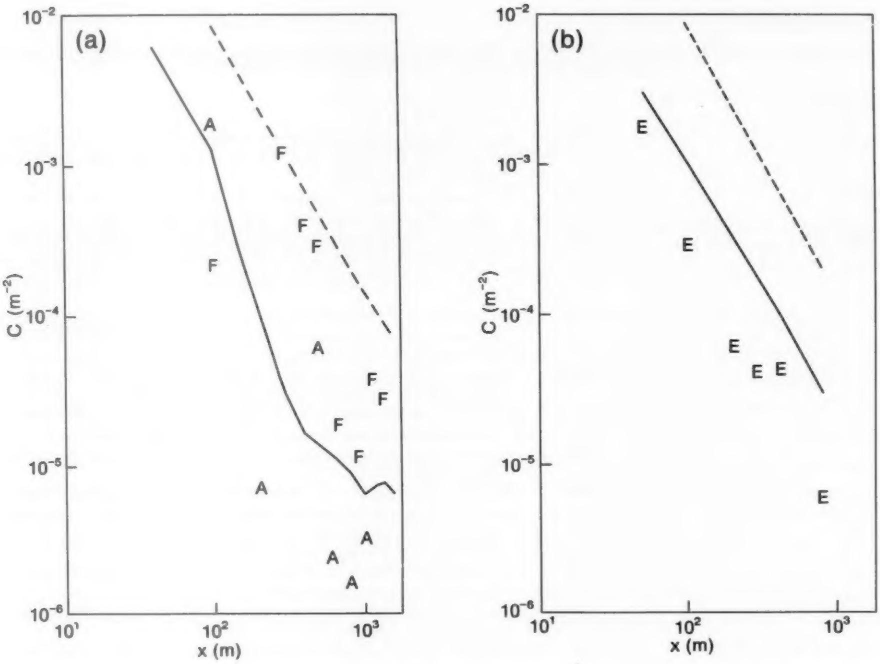

Figure 6. Variation of concentration with distance downwind for a source on (a) the summit upwind of the valley and (b) the floor of the valley (taken from Thomson 1986a). x is the downwind distance and C is the concentration normalized by Q/U, Q being the source strength and U the 8 m summit wind speed. The solid line is the random walk prediction, the dashed line is a prediction from Turner's (1969) Gaussian plume model using the summit wind speed, and A, E and F denote observed concentrations from different experiments.

motion of pairs of particles is due to Batchelor (1952), but it is only comparatively recently (Durbin 1980) that this has been exploited by simulating the motion of particle pairs numerically. Such models have had some success in predicting concentration fluctuations in simple situations (see for example Durbin (1982) who considered concentration fluctuations in homogeneous wind tunnel turbulence). However, there is no consensus about how such models should be formulated (see for example Egbert and Baker (1984), Sawford (1984) and Thomson (1986b)). Their application to the problem of obtaining quantitative predictions of σ_c in atmospheric flows is a matter for the future.

5. Conclusion

Random walk models are a promising approach to the problem of the dispersion of a passive substance in the atmospheric boundary layer. Although simple in concept, they avoid many of the problems inherent in other techniques. They are particularly suited to situations where the flow properties are inhomogeneous (e.g. the convective boundary layer); many other techniques fail in these situations. Although they involve a number of assumptions and cannot be justified in any fundamental way, so far they show good agreement with experimental data. It seems likely that such models will be increasingly exploited in the future.

Acknowledgement

The author would like to thank the Royal Meteorological Society for permission to reproduce Fig. 5.

References

Barad, M.L. 1958 Project Prairie Grass, a field program in diffusion, Vol. I. Geophysics Research Paper 59, Air Force Cambridge Research Centre. AFCRC-TR-58-235(I).

Batchelor, G.K. 1952 Diffusion in a field of homogeneous turbulence. II. The relative motion of particles. *Proc Cambridge Philos Soc*, **48**, 345–362.

Callander, B.A. 1986 Short range dispersion within a system of regular valleys. *In* Proceedings of the Fifteenth NATO/CCMS International Technical Meeting on Air Pollution Modelling and its Application. London, New York, Plenum Press.

de Baas, A.F., van Dop, H. and Nieuwstadt, F.T.M. 1986 An application of the Langevin equation for inhomogeneous conditions to dispersion in a convective boundary layer. *Q J R Meteorol Soc*, **112**, 165–180.

Deardorff, J.W. 1978 Closure of the second- and third-moment rate equations for diffusion in homogeneous turbulence. *Phys Fluids*, **21**, 525–530.

Durbin, P.A. 1980 A stochastic model of two-particle dispersion and concentration fluctuations in homogeneous turbulence. *J Fluid Mech*, **100**, 279–302.

1982 Analysis of the decay of temperature fluctuations in isotropic turbulence. *Phys Fluids*, **25**, 1328–1332.

Egbert, G.D. and Baker, M.B. 1984 Comments on paper 'The effect of Gaussian particle-pair distribution functions in the statistical theory of concentration fluctuations in homogeneous turbulence' by B.L. Sawford (*Q J R Meteorol Soc*, **109**, 339–353). *Q J R Meteorol Soc*, **110**, 1195–1199.

Langevin, P. 1908 Sur la théorie du mouvement brownien. *Comptes Rendus Hebdomadaires des Séances*, Paris, **146**, 530–533.

Ley, A.J. and Thomson, D.J. 1983 A random walk model of dispersion in the diabatic surface layer. *Q J R Meteorol Soc*, **109**, 867–880.

Mason, P.J. and King, J.C. 1984 Atmospheric flow over a succession of nearly two-dimensional ridges and valleys. *Q J R Meteorol Soc*, **110**, 821–845.

Pasquill, F. and Smith, F.B. 1983 Atmospheric diffusion, 3rd edition. Chichester, Ellis Horwood Ltd.

Sawford, B.L. 1984 Reply to comments by Egbert and Baker. *Q J R Meteorol Soc*, **110**, 1199–1200.

Taylor, G.I. 1921 Diffusion by continuous movements. *Proc London Math Soc*, Ser 2, **20**, 196–211.

Thomson, D.J. 1984 Random walk modelling of diffusion in inhomogeneous turbulence. *Q J R Meteorol Soc*, **110**, 1107–1120.

1986a A random walk model of dispersion in turbulent flows, and its application to dispersion in a valley. *Q J R Meteorol Soc*, **112**, 511–530.

1986b On the relative dispersion of two particles in homogeneous stationary turbulence and the implications for the size of concentration fluctuations at large times. *Q J R Meteorol Soc*, **112**, 890–894.

(1987) Criteria for the selection of stochastic models of particle trajectories in turbulent flows. (Submitted to *J Fluid Mech*).

Turner, D.B. 1969 Workbook of atmospheric dispersion estimates. US Department of Health, Education and Welfare, Public Health Service Publication No. 999-AP-26.

van Dop, H., Nieuwstadt, F.T.M. and Hunt, J.C.R. 1985 Random walk models for particle displacements in inhomogeneous unsteady turbulent flows. *Phys Fluids*, **28**, 1639–1653.

Willis, G.E. and Deardorff, J.W. 1976 A laboratory model of diffusion into the convective planetary boundary layer. *Q J R Meteorol Soc*, **102**, 427–445.

1981 A laboratory study of dispersion from a source in the middle of the convectively mixed layer. *Atmos Environ*, **15**, 109–117.

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The skill of dynamical long-range forecasts*

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Summary

The Meteorological Office 5-level general circulation model has been used to investigate the skill of winter-time long-range forecasts. Even with climatological sea surface temperatures, the large-scale features of the flow are found, on average, to have a small but significant correlation with the real atmospheric evolution out to about 20 days. The use of observed tropical sea surface temperatures improved the forecast in four out of five years.

1. Introduction

It is well established that the prediction of instantaneous weather patterns is impossible beyond about 10–15 days. The upper limit of deterministic predictability has been estimated by calculating how quickly small differences in the initial state (representing the uncertainty in our knowledge of the true state of the atmosphere) grow to reach saturation value. The lower limit is found by comparing the model evolution directly with the real atmosphere. Beyond 10–15 days some large-scale features of the circulation may remain predictable, but on average the degree of skill is likely to be small.

It appears that the degree of skill obtainable may depend rather heavily on the initial conditions. If this is the case, then a large number of integrations from independent initial conditions are required before the true potential of the forecasts can be assessed. Furthermore, the limitations of even the most up-to-date models are such that, over a period of 30–50 days, the model drifts towards an average state which differs from the real climatology by an amount comparable with typical departures from that climatology. This means that a model is useful for long-range forecasting experiments only if it has a realistic climatology.

In 1978 the Meteorological Office began systematically to produce 50-day experimental forecasts with a hemispheric version of the 5-layer general circulation model described by Corby *et al.* (1977). (Routine global analyses were not available at the time.) These forecasts were carried out once or twice a month from January 1978 to January 1982. In addition, ten forecasts from the winters of 1974/75 to 1977/78 were available.

In spite of the low vertical resolution of the model and the relatively simple parametrization of physical processes (by present-day standards), the winter climatology of the model is realistic in terms of the time-mean flow and the behaviour of transients. Therefore the set of winter forecasts provides a basis for testing the skill of dynamical forecasts from a wide range of initial conditions.

A correct prediction of, say, 500 mb height anomaly over the United Kingdom would be a useful forecast, even if the magnitude was much less than that observed. Therefore it is preferable to use an anomaly correlation as a measure of skill rather than the root-mean-square difference since emphasis needs to be placed on the phase of the anomalies rather than their magnitude. The anomaly correlation is defined as the correlation between the forecast anomaly (i.e. the difference between the forecast and the model's climatology) and the corresponding observed anomaly. This means that a perfect forecast has a correlation of 1.0, whereas if the correlation is zero the forecast has no skill. The model climatology has been constructed by averaging seventeen 50-day integrations from initial conditions separated by at least 5 days and spanning 8 winters.

* An abridged version of a paper by Mansfield (1986) which appeared in the Quarterly Journal of the Royal Meteorological Society.

The forecast results from integrations with climatological Sea Surface Temperatures (SSTs) are discussed in section 2, while in section 3 an attempt is made at assessing the impact of observed SSTs.

2. Forecast skill with climatological sea surface temperatures

Fig. 1(a) shows the daily anomaly correlation averaged over the 18 forecasts which used climatological SSTs. The correlation is significantly greater than zero at the 5% level up to and including day 16. Therefore, for this model, there is a small degree of skill observable in daily forecasts up to about 2 weeks.

There is evidence that by considering time-meaned fields instead of daily forecasts, the signal to noise ratio is increased because the unpredictable (i.e. synoptic scale) part of the flow is filtered out — thus allowing an extension of the period over which skill can be detected. This is illustrated by Fig. 1(b) which shows the correlation of 15-day mean forecasts, averaged over the 18 forecasts (the correlation has been calculated for overlapping 15-day means, centred 5 days apart, commencing with days 1–15). Note that the skill remains significantly different from zero for only about 4 days longer than for the daily forecasts. This is a disappointing result, as it might have been expected that the small degree of skill shown in the daily forecasts would have been amplified to a greater extent. One reason for this is that the small degree of skill remaining after the first 10 days or so is not uniformily distributed. Three of the forecasts showed some skill throughout the 50 days, whereas in five cases the anomaly correlation fell to zero within 10 days. Any subsequent negative correlations in the poor forecasts will be amplified by the averaging, as well as the positive correlations in the successful forecasts. The large dispersion in the skill of the forecasts at the extended range is not just due to sampling fluctuations but is a result of genuine differences in predictability between different atmospheric states.

In order to concentrate on those forecasts which exhibit most skill, those eight forecasts which had positive correlations up to or beyond the 16–30 day mean were chosen for further analysis. Since the mean-sea-level pressure (MSLP) is perhaps more easily interpreted in terms of weather, this has been chosen as the field to be used to illustrate the maximum skill obtainable with the model. Results for the limited area surrounding the United Kingdom used for statistical long-range forecasts at the Meteorological Office (30–87.5° N, 45° W–25° E) were computed to facilitate interpretation in terms of synoptic patterns. Since the skill is due to the largest scales of motion, values are similar to those of the hemisphere as a whole.

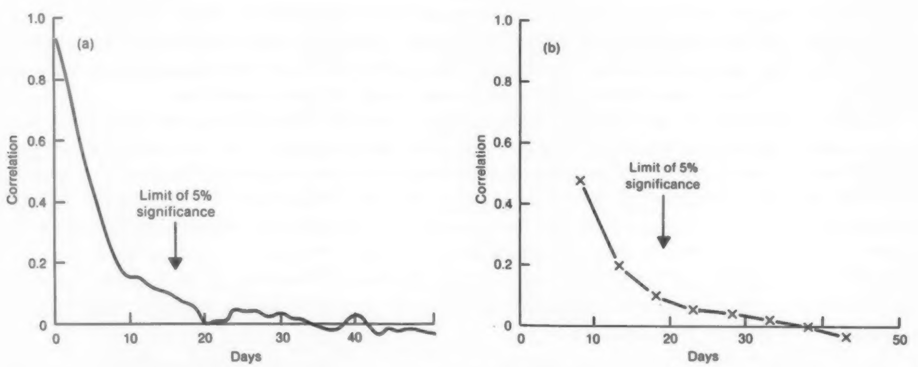

Figure 1. (a) Daily and (b) 15-day-mean anomaly correlations, averaged over 18 winter forecasts for the 500 mb height in the region 30–85° N.

Fig. 2 shows the anomaly correlation of 15-day-mean MSLP for the eight most skilful forecasts and all eighteen forecasts for the region. Also included is the average skill of persistence forecasts based on the mean observed anomaly for the 15 days up to and including day zero of each of the 18 forecasts. Overall, the 15-day-mean model forecasts are better than persistence only for the first 15-day mean. However, the best eight model forecasts display skill above that of persistence to beyond day 30. These more skilful forecasts tend to be associated with greater than average persistence in the real data, but the difference in persistence anomaly correlation between these runs and all 18 runs is not significant at the 5% level. Thus persistence alone cannot explain the extended predictability.

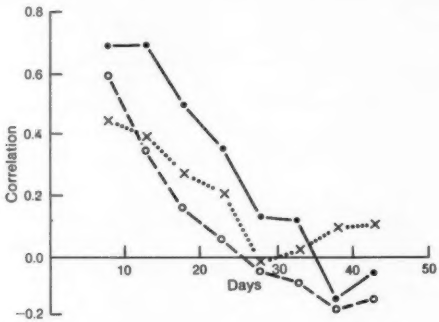

Figure 2. Anomaly correlations of 15-day-means of mean-sea-level pressure for the area 30–87.5°N, 45°W–25°E for all 18 forecasts (dashed line), the best 8 forecasts (solid line), and the persistence forecasts averaged over all 18 cases (dotted line).

An illustration of what the degree of skill of one of the better forecasts represents in synoptic terms is given in Fig. 3 which shows the real and model mean MSLP anomalies for 1–15 and 16–30 January 1978 (corresponding to days 1–15 and 16–30 of the model forecasts). The anomaly correlations in this particular case, 0.43 and 0.66 for the first and second periods, are equalled or surpassed by four other forecasts. At first sight the forecasts do not look very good, particularly during the first period. However, the forecast pressure anomaly would produce a generally westerly anomaly in the wind over much of the region and this would suggest a predominantly mobile situation with probably above normal temperatures at least in the south of the British Isles. In the second period, the anomaly was more cyclonic and more north-westerly in both the model and reality. Thus the forecast correctly indicated a colder and wetter second half-month, especially in the north of the United Kingdom. The increased westerly gradient in the second period would have implied a stronger-than-average temperature contrast between north and south and, coupled with the above average precipitation, would have suggested more snow than usual in the north. In fact, some unusually heavy snowfall did occur in northern Britain in the second half of the month.

To be able to utilize the higher degree of skill in some forecasts it is necessary to know, a priori, which forecasts are likely to be successful. One possibility is that these forecasts would display above average short-range skill, but this turned out not to be the case. There is no indication of above average daily skill in the first 6 days, even in the largest scales, in those forecasts with skill at extended range.

3. The effect on skill of including observed sea surface temperatures

There is ample evidence that SSTs affect the atmospheric circulation, though experience suggests that the atmosphere is more responsive to tropical SST anomalies than it is to those in mid-latitudes. For

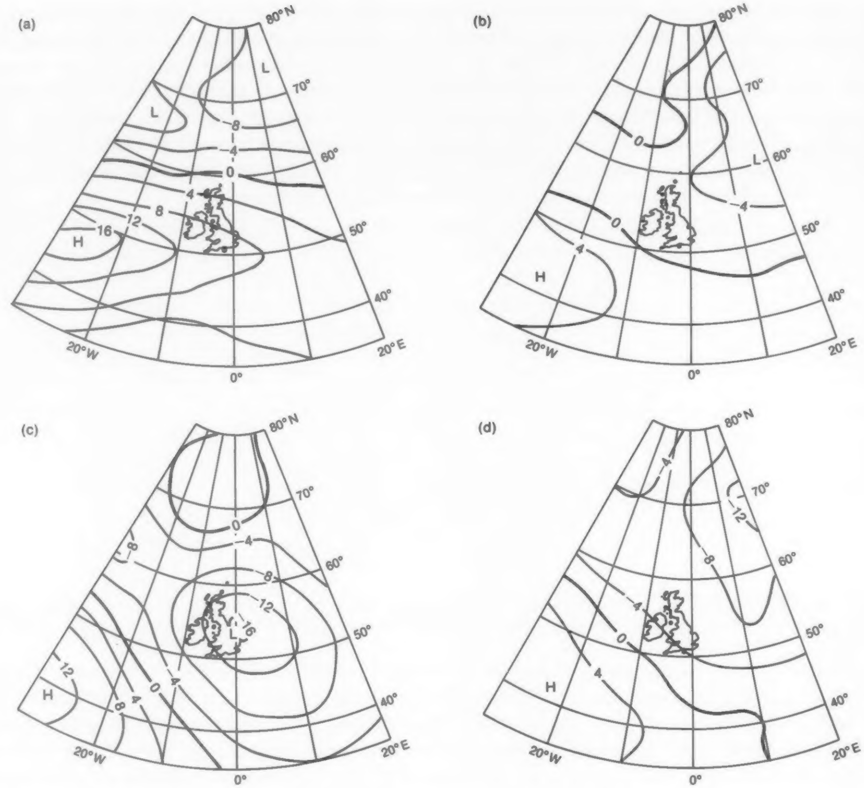

Figure 3. (a) Observed and (b) forecast mean-sea-level pressure anomalies (mb) for 1–15 January 1978. (c) and (d) are as (a) and (b) respectively, but for 16–30 January 1978.

example, it has been found that, in terms of the surface pressure field, the mid-latitude response of the model used in this investigation is likely to be 3–4 times greater for tropical than mid-latitude forcing. Certainly, sensitivity experiments have shown that mid-latitude SST anomalies have little consistent beneficial effect on forecast skill, but the large response to tropical SSTs suggests that the use of observed SSTs rather than the climatological values would lead to an improvement in forecast skill.

Nine of the forecasts were rerun with the observed SST anomalies south of 30° N. The values used were the average for January of each year involved, and were held fixed throughout the forecast. Where more than one forecast was performed for a given winter, the same SSTs were used in each.

The results in terms of 15-day-mean anomaly correlations of the 500 mb height show that using realistic SSTs improved the correlations averaged over the whole forecast by more than 0.1 in four experiments, in three they were marginally improved, one was made slightly worse, and in one it was made very much worse. Averaged over all forecasts, the improvement in correlation of only 0.06 is clearly not statistically significant. However, the worst three results all occurred in the same winter, i.e. with the same SST anomaly. Fig. 4 shows that, if the 15-day-mean anomaly correlations are averaged

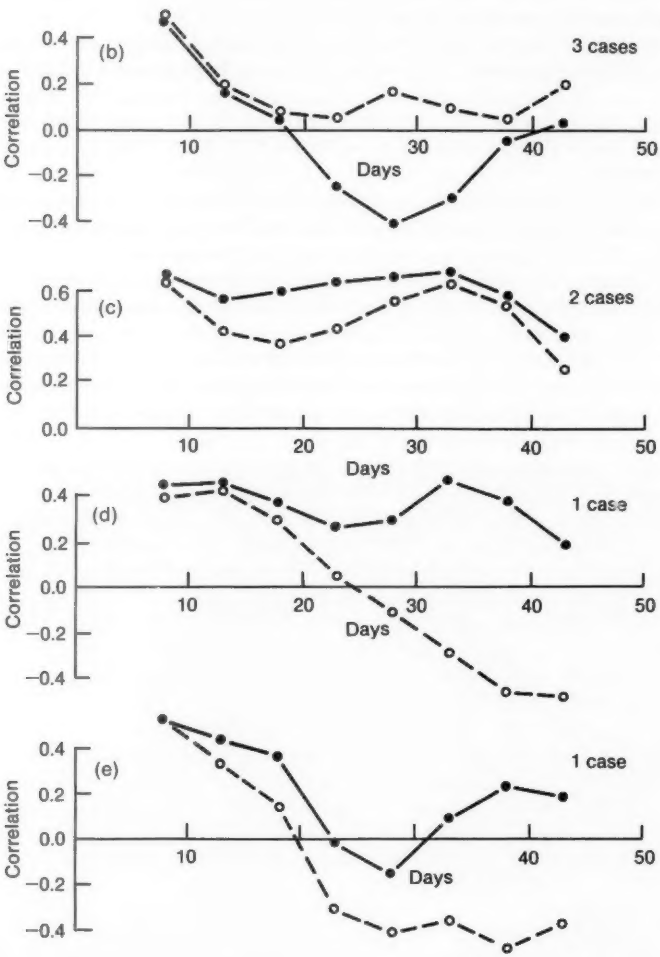

Figure 4. Anomaly correlation of 15-day-mean forecasts of 500 mb height for 30–85° N for runs with observed (solid line) and climatological (pecked line) SSTs. Results averaged over runs with the same SSTs for (a) 1975, (b) 1976, (c) 1977, (d) 1978 and (e) 1981.

for each SST pattern used, there is a clear improvement in skill in four out of five years. As might be expected, if the improvement in skill is real, there is a tendency for the improvement to increase with time. The exceptions are 1976 when there was no improvement and in 1977 where the forecasts with climatological SSTs already showed a large degree of skill.

These results suggest that the use of observed tropical SSTs will, in general, increase the skill of 50-day forecasts. There will, of course, be occasions when the reverse is true. This can occur for several reasons:

(a) The SST observations may not be representative enough, though this problem should decrease with increased reliability of satellite measurements.

(b) The effect of SSTs may be misrepresented due to inadequate parametrization of the surface exchanges or of deep convection, or due to an error in the large-scale flow field.

(c) If the forcing is weak, chance variations in the mid-latitude flow may overwhelm the effect of the SST anomaly.

4. Concluding remarks

The results presented here suggest that, on average, model forecasts of the large-scale features of the flow have a small but significant correlation with the real atmospheric evolution out to about 20 days.

The degree of extended-range skill is not uniformly spread between forecasts; five forecasts were more skilful than persistence to beyond three weeks, whereas seven were better than persistence for less than 10 days. Although it is difficult to prove, it is believed that the apparent extended skill in some forecasts is genuine and not the result of chance sampling fluctuations. An important aspect of future work will be to search for a way of detecting, a priori, forecasts which are likely to prove more skilful. To this end, experiments are being carried out in the Synoptic Climatology Branch of the Meteorological Office with ensembles of forecasts from similar initial conditions, and relationships are being sought between the degree of dispersion of the forecasts and their skill.

In the absence of other than climatological mean boundary forcing, even the largest scales must eventually become unpredictable. If, however, anomalous forcings such as those due to SST anomalies are included, this restriction may be removed and some forecast skill may be available as long as the anomalous forcing is correctly modelled. The experiments described here do show some increase in skill when observed (as opposed to climatological) SSTs are included, and in spite of the hemispheric domain this increase in skill is, on occasion, quite substantial.

Other experiments, described in Mansfield (1986), suggest that the atmosphere may be particularly sensitive to SSTs in certain areas, such as the western part of the tropical oceans. In these regions anomalies as small as 1 K or less have a significant effect on the forecast. This is close to the limit of accuracy of SST measurements in these areas and indicates that great care is needed in ensuring that the best possible SST analyses are used. It also indicates the degree of accuracy needed in ocean models before a coupled ocean–atmosphere model can be used to attempt seasonal forecasts.

These results have been achieved with a model of limited short-range skill and known deficiencies, such as a hemispheric domain and simplified physics. Outside the winter season, the model has a climatology too poor to be used for long-range forecasts. It remains to be seen what degree of skill can be obtained using global models (based on the operational and climate models) and how this skill varies with season.

References

Corby, G.A., Gilchrist, A. and Rowntree, P.R. 1977 The United Kingdom Meteorological Office five-level general circulation model. *Methods Comput Phys*, **17**, 67–110.

Mansfield, D.A. 1986 The skill of dynamical long-range forecasts, including the effect of sea surface temperature anomalies. *Q J R Meteorol Soc*, **112**, 1145–1176.

Awards

L.G. Groves Memorial Prizes and Awards

The presentation of the L.G. Groves Memorial Prizes and Awards for 1985 was made on 8 January 1987 by Major J. Groves who is the great-nephew of the founders of the memorial fund established in memory of Louis Grimble Groves. Air Vice-Marshal J.R. Walker, CBE, AFC, FBIM presided and Air Commodore P. King, CBE, FBIM (Inspector of Flight Safety) read the citations. The ceremony was also attended by members of the Groves family and representatives of the RAF and the Meteorological Office. This was the first time that the presentation had taken place in the Meteorological Office at Bracknell.

Mr J. Findlater, who has recently retired from the Meteorological Office, was awarded the Meteorology Prize for his work on fog, particularly sea fog which affects airfields in the Moray Firth area. He devised and directed 'Project Haar', an experimental study of sea and coastal fog around north-east Scotland involving a variety of new measuring techniques as well as the use of the Hercules aircraft of the Meteorological Research Flight (MRF). The results are already proving of value to local forecasters. His deep interest in aviation has been reflected by the many hours he has flown as Mission Scientist during his investigations, and by his dedication to aviation safety in much of his own work; typical of this is his membership of the UK Flight Safety Committee as representative of the Royal Meteorological Society.

The Meteorological Observer's Award was presented to Mr P. Joy of the Meteorological Office for his invaluable work as an observer on the MRF Hercules aircraft. He has flown over 1750 hours on scientific missions and there are few experiments of recent years that have not benefited from his reliability and dedication.

Mr J. Findlater, winner of the Meteorology Prize, receives his prize from Major J. Groves.

Mr P. Joy, winner of the Meteorological Observer's Award, receives his award from Major J. Groves.

Major J. Groves with Wing Commander M.W. Ball, who received the Air Safety Prize on behalf of the Tornado Operational Evaluation Unit, and Flight Lieutenant G.B. Jones, winner of the Ground Safety Award.

The Air Safety Prize was awarded to the Tornado Operational Evaluation Unit at Boscombe Down for their Head-Up Autopilot and Flight Director System. The Unit was tasked to move the indicators and selectors for the autopilot and flight director system in the Tornado to a position where they were in the pilot's field of view. The modification was designed, tested and approved, and it was so successful that it was installed in the aircraft which competed so successfully in the 1985 Strategic Air Command Bombing Competition. In developing the modification the Unit demonstrated thoroughness, both in research and engineering, in providing a solution which exceeded the criteria specified.

Flight Lieutenant G.B. Jones, also from Boscombe Down, received the Ground Safety Award for his computer produced safety trace for air weapons ranges. He devoted over 1000 hours, much of it in his own time, to developing the computer program which has now been authorized for unrestricted use in the work of the Armament Division at Boscombe Down. The Ordnance Board are examining the wider application of the program to other ranges.

Review

Intrinsic geodesy, by A. Marussi, translated from the Italian by W.I. Reilly. 160 mm × 240 mm, pp. xvii + 219, *illus*. Berlin, Heidelberg, New York, Tokyo, Springer-Verlag, 1985. Price DM 160.00.

Modern geodesy owes much to two papers, published after the Second World War, which introduced the global and local treatments of the earth's gravity field, namely M.S. Molodensky's *Investigations of the fundamental problems of geodetic gravimetry* and Antonio Marussi's *Fondementes de géométrie différentielle absolue du champ potential terrestre*. The difficult task of determining the form of the earth's surface from gravimetric data was treated by Molodensky as a boundary-value problem of potential theory. Marussi formulated the problem as one to which modern differential geometry could be applied, thus employing a vector calculus which has been termed 'intrinsic', 'absolute' or 'autonomous' by various writers.

Intrinsic geodesy reproduces 21 of Marussi's papers grouped under the headings 'Fundamentals of intrinsic geodesy' (6 papers), 'Structure of the gravity field and Laplace's equation' (2 papers), 'Principles of intrinsic geodesy applied to the normal reference field' (3 papers), 'Propagation of light in continuous isotropic refracting media' (2 papers) and 'Posthumous work' (1 paper with C. Chiaruttini). The book starts with a short appreciation of the life and work of Marussi by Professor A. H. Cook, introductory remarks by the author, who died in 1984 before the book was completed, and a preface by Dr W.I. Reilly, who translated many of the original papers from Italian into English. The book ends with an appendix on the vertical homographies of Burali-Forti and Marcolongo by Dr W.I. Reilly, a list of Marussi's scientific papers, and an obituary of Marussi by Professor H. Moritz.

Intrinsic geodesy is not a book for the mathematically faint-hearted, and its links with meteorology are less direct than they are with branches of the earth sciences that deal with gravitational tides and the structure of the solid earth. But theoretical geodesists will find much of interest in *Intrinsic geodesy*, and other mathematically-qualified scientists who read the book will have their appreciation of the subject greatly enhanced.

R.Hide

Radar photograph — 18 March 1987 at 0800 GMT

The display shows radar information from the United Kingdom, Republic of Ireland, France and Switzerland superimposed on a background field showing regions of 'cold' cloud as indicated by Meteosat. The data from the mainland of Europe have recently become available at the Meteorological Office, Bracknell following considerable software development within their Operational Instrumentation Branch.

The European Weather Radar Project, COST 73 (Co-operation in Science and Technology), is a joint project involving most countries in Europe. One of the aims is to study how a radar network might be set up across Europe. The addition of data from Northern Ireland and the Netherlands (De Bilt) is imminent, and data from the first two radars in a German network, as well as additional radars within the United Kingdom, should be available in 1988.

The picture below was taken as a cold front moved steadily southwards across western Europe ahead of a very cold polar north-westerly airstream. The rainfall, in two main bands, corresponds well with the associated region of cold cloud. Over the British Isles, showers are observed over Wales and western Ireland, whilst over the north Midlands there is a trough line present which later, following daytime heating, produced thunderstorms and hail over southern England.

Key. Cloud: blue < −15 °C to −40 °C, green < −40 °C. Rainfall intensity: magenta 0.3 to 1 mm h^{-1}, cyan 1 to 3 mm h^{-1}, red 3 to 10 mm h^{-1}, yellow 10 to 30 mm h^{-1} and white > 30 mm h^{-1}. Data resolution 5 km. Radar boundaries are shown white. (Note that permanent clutter close to the French radar sites is removed, but other clutter is not cancelled as is done in the United Kingdom).

Meteorological Magazine

GUIDE TO AUTHORS

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